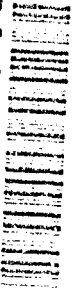


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EFFECT OF POWERFUL OBLIQUE HF WAVES ON IONOSPHERIC D-LAYER ABSORPTION

R. M. Bloom

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2901 28th Street, #300
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April 13, 1993

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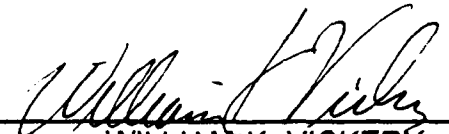
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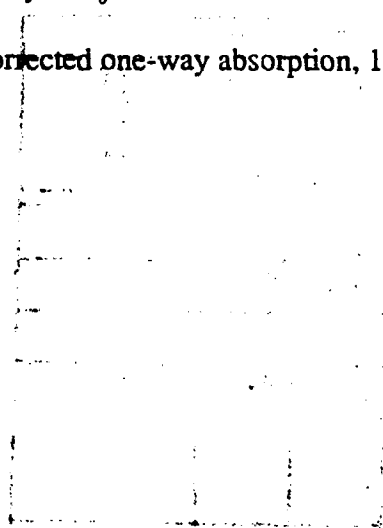
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SUMMARY

A simple model of D-layer ionospheric heating in the presence of strong, high frequency (HF) radio waves is used to predict the anomalous, nonlinear wave absorption due to collisional and recombination effects induced by the indirect signal. It is found that little anomalous absorption occurs until effective radiated power (ERP) approaches 100 dBW; further increases in power of several dB beyond this 100 dBW threshold are frustrated by a comparable increase in self-induced, one-way absorption. This trend of increasing absorption with increasing transmitter ERP has considerable implications for design of communication or radar systems that use ultra-powerful, high-gain HF transmitters.

STATEMENT OF PROBLEM

Over the last several years, proposals for very powerful HF radar transmitters have involved radiated power levels that approach or exceed the threshold for nonlinear interactions to occur between the radio wave and the ionospheric plasma ($\text{ERP} \geq 90\text{--}95\text{ dBW}$).

In the ionospheric E- and F-layers powerful HF waves produce a complex of wave-medium interactions due to plasma diffusion along geomagnetic field lines [Bloom, et al., 1991]. In the D-layer ($\sim 60\text{ km}$) powerful HF waves influence the medium largely through nondiffusive electron heating. This results in (a) change in the electron-neutral collision frequency and (b) change in the electron number density through temperature-dependence of electron recombination and attachment rates. The important consequence for HF propagation is that (a) and (b) cause the incremental nondeviative absorption of the layer to increase. Thus the overall attenuation suffered by a plane wave (ray) traversing the D-layer on a two-way path may be markedly greater than that predicted by the linear theory.

This is the crucial question concerning HF radar transmitters: does an increase in ERP of, say, 5 dB (in the vicinity of the nonlinearity threshold of the D-layer) lead to a comparable increase in the overall wave attenuation? As we demonstrate, the answer is a qualified "yes."

The incremental absorption is proportional to both the electron collision frequency and to the electron number density. In the D-layer, both of the quantities are proportional to electron temperature (which itself increases with the local electric field intensity). Using simple models for these dependencies, ambient daytime D-layer conditions, and an inverse-distance field law, we have computed the first-order, field-induced perturbations in electron temperature, electron collision frequency, and electron density along an 18° ray path at 15 MHz. (We have followed Ginzburg [1970] and Gurevich [1978].)

The perturbed values are used to recompute a "modified" wave absorption along the ray path. We have done this for four values of transmitter ERP--90, 95, 100, and 105 dBW. These approximate calculations indicate that an increase in HF power of 5 dB above the 100 dBW level is met by almost as much in increased one-way absorption through the wave-medium interaction effects. On a two-way radar path, therefore, the advantages of the increased transmitter power are frustrated by the upward trend in total D-layer absorption. (See Fig. 1.)

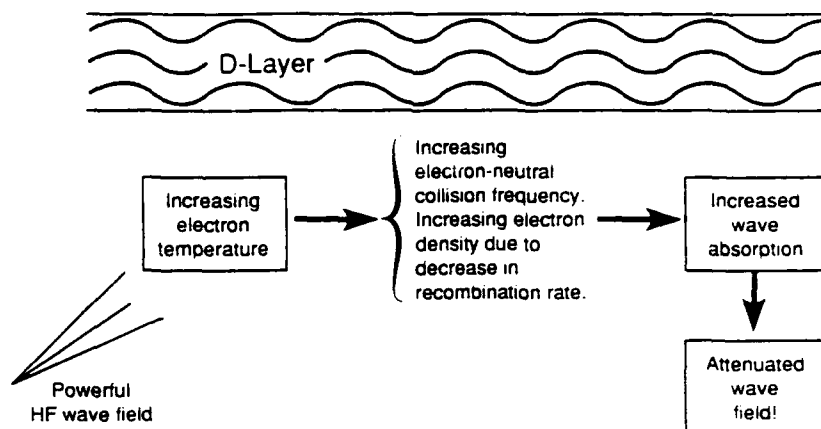


Figure 1. Nonlinear self-effect of powerful HF wave in the D-layer.

LINEAR THEORY

In an isotropic medium (e.g., the lower ionosphere, neglecting the geomagnetic field at HF frequencies, $\omega \gg \omega_H$), the complex refractive index is given by the Appleton Formula:

$$(A) \quad n^2 = (\mu - i\chi)^2 = 1 - \frac{X}{1 + Z^2} - \frac{iXZ}{1 + Z^2}$$

$$(B) \quad \text{where} \quad X = \frac{\omega_p^2}{\omega^2}$$

$$Z = \frac{\nu}{\omega}$$

ν = electron collision frequency

$\omega_p^2 = N_e^2 / \epsilon_0 m_e$ (the "plasma frequency")

N = electron density (cm^{-3})

e = electronic charge

m_e = electron mass

$\omega = 2\pi f$, f is the HF wave frequency.

The equation for a plane wave solution of Maxwell's equations, traveling in the x-direction, is

$$\bar{E} = E_0 \exp \left[i \left(\omega t - \frac{\omega}{c} n x \right) \right]$$

or

$$E = E_0 \exp[\kappa x] \cdot \exp \left[i \left(\omega t - \frac{\omega}{c} \mu x \right) \right] ,$$

where $\kappa = \frac{\omega}{c} \cdot \text{Im}(n)$ measures the decay of amplitude per unit distance and is called the incremental absorption of the medium; it is measured in nepers/distance, where 1 neper = 8.7 dB.

Using (A) and (B) we obtain

$$\kappa = \frac{\omega}{c} \frac{1}{2\mu} \frac{XZ}{1+Z^2} = \frac{e^2}{2\epsilon_0 m_e c} \cdot \frac{1}{\mu} \frac{N\nu}{\omega^2 + \nu^2} .$$

So-called *nondeviative* absorption occurs in the D-layer where $\mu \approx 1$ and $N\nu$ is large. In units of dB/km, we obtain the following expression for incremental, nondeviative absorption [Knapp and Fischer, 1970]:

$$a = \frac{4.6 \times 10^4 N\nu g}{(\nu g)^2 + (\omega h)^2} \text{ dB/km} , \quad (1)$$

where g and h are correction factors that account for the velocity-dependence of electron collision frequency.

The total one-way absorption for a ray incident upon the D-layer with angle θ is

$$A^{\text{total}}(z) = \int_0^z a(z) dz / \cos \theta \text{ dB} ,$$

where θ is a more complicated function of z for a spherical earth. (We have used flat-earth calculations over relatively short path lengths. See Fig. 2.)

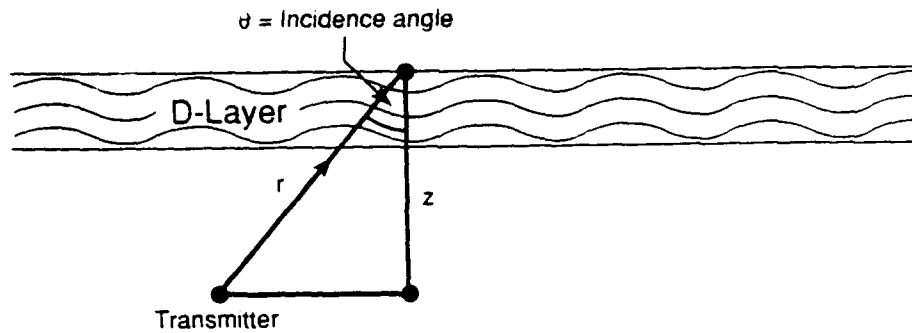


Figure 2. Propagation geometry.

The electric field will be attenuated by the factor $\exp[-A^{total}(z)/8.7]$ due to non-deviative absorption along the ray path.

CALCULATION OF NONLINEAR WAVE ABSORPTION

In order to predict possible self-attenuation of the strong HF wave, we must investigate the dependence of the quantities ν and N in Eq. (1) on electron temperature, T_e .

We take the height-dependence of the ambient electron-neutral collision frequency to be $\nu_{em}^0(z) = 1.6 \times 10^{11} e^{-15z}$, with z in km. An ambient daytime profile for the electron density $N(z)$ is shown in Fig. 3. These ambient values are used to calculate from Eq. (1) the cumulative absorption $A^{total}(z)$ along the given ray path. The peak electric field, uncorrected for temperature-dependent wave absorption, is $E = E_0 \exp[-A^{total}(z)/8.7]$. The peak field amplitude E_0 is the simple, free-space, far-field approximation

$$E_0 \sim \sqrt{\frac{Z_0 PG}{4\pi R^2}}$$

where PG is the effective radiated transmitter power multiplied by the antenna gain; Z_0 is the impedance of free space; and R is the distance along the ray path from the source. This quantity $E(z)$ is subsequently used to compute a first-approximation to the change in electron-temperature at each height z .

In the absence of heat-conduction and diffusion, the electron temperature at a given height z is governed by the differential equation [Field and Warber, 1985]:

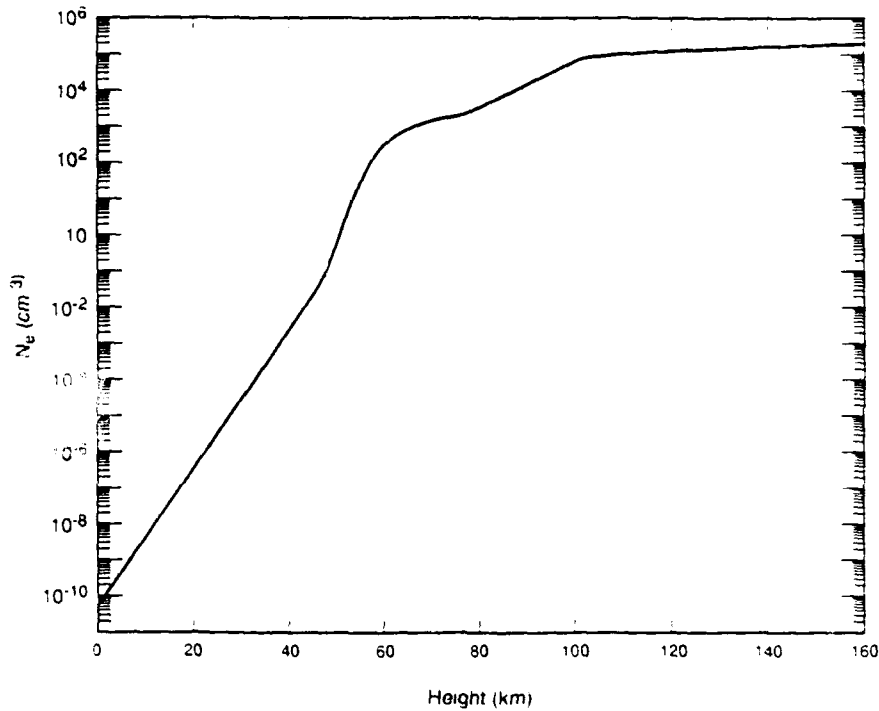


Figure 3. Ambient daytime electron density profile $N_e(z)$.

$$\frac{dT_e}{dt} = \delta \nu(T_e; z) T_0 \left[\frac{E_0^2(z)}{E_p^2} + 1 - \frac{T_e}{T_0} \right],$$

where

$$E_p^2 = \frac{3KT_0 m_e \delta (\omega^2 + \nu^2)}{e^2},$$

E_p is the "characteristic plasma field" [Gurevich, 1978]

$T_e(t)$ is the electron temperature

T is the time after the application of the field E

K is Boltzmann's constant

T_0 is the ambient electron temperature

m_e is the electron mass δ is fractional energy lost by an electron in one collision

ν is electron collision frequency.

Regardless of the form of the collision frequency $\nu(T)$, for large times $t \gg \left(\frac{1}{\delta\nu}\right)$ and field E on the order of E_p the steady state will be achieved:

$$\frac{T_e}{T_0} = 1 + \frac{E_0^2}{E_p^2}, \quad (2)$$

which is the factor by which the field E_0 increases the temperature T_e to a first approximation. This is a nonlinear implicit relation for T_e , insofar as E_p^2 depends on $\nu = \nu(T_e)$. Depending on the predominant collisional processes, $\nu(T_e)$ will be proportional to some power of T_e .

In the ionospheric D-layer, electron collisions with neutral molecules dominate and $\nu \equiv \nu_{em}(T_e)$. Unfortunately, there is in the existing literature a panoply of seemingly dissimilar formulas for $\nu_{em}(T_e)$. For example, Gurevich [1978] gives $\nu_{em} \sim T^{5/6}$, but Ginzburg [1970] uses $\nu_{em} \sim T^{1/2}$. Banks and Kockarts [1973] give what is now regarded as the correct expression for ν_{em} :

$$\nu_{en} = 1.8 \times 10^{-11} N_m T_e \left[1 + \frac{2}{\sqrt{T_e}} \right],$$

where N_m is the neutral density and the correction term $\frac{2}{\sqrt{T_e}}$ accounts for collisions with O_2 molecules.

In the lower ionosphere, where $T_e \sim 250^\circ$, this expression is quite close to that given in Knapp and Fischer [1970]:

$$\nu_{em} = 2.0 \times 10^{-11} N_m T_e^{1.0},$$

which we adopt for its obvious simplicity [Field, 1989].

Solving Eq. (2) by iteration, we obtain the fractional change in electron temperature $\frac{T_e}{T_0} = 1 + \frac{E_0^2}{E_p^2}$ and recalculate everywhere the temperature-corrected collision frequency

$$\tilde{\nu}_{em} = \nu_{em} \cdot \left(\frac{T_e}{T_0} \right)^{1.0} \text{ and the temperature-corrected incremental absorption}$$

$$\tilde{a} = \frac{4.6 \times 10^4 N(z) \tilde{\nu}_{em}(z)}{(\tilde{\nu}_{em} g)^2 + (\omega h)^2}$$

The comparison, then, of the cumulative absorption,

$$A^{tot} = \int_0^z a(z) dz / \cos \theta \quad \text{to} \quad \tilde{A}^{tot} = \int_0^z \tilde{a}(z) dz / \cos \theta \quad ,$$

illustrates the self-attenuation of the strong HF wave E in its traverse of the D-layer.

This comparison of the cumulative, one-way absorption of a 15 MHz ray along an 18° path is shown in Fig. 4. Four power-gain products--90, 95, 100 and 105 dBW--are compared for the corresponding effect on collisional absorption. Figure 5 shows the corresponding fractional increase T_e / T_0 in electron temperature as a function of height. The factor T_e / T_0 is precisely the factor by which the electron collision frequency increases.

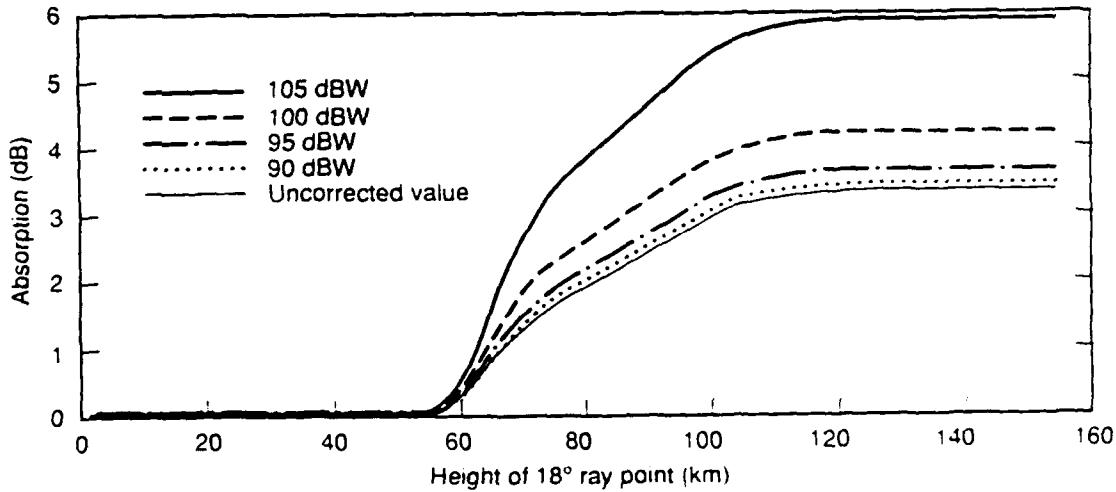


Figure 4. One-way total absorption, 15 MHz, 18° ray, daytime, corrected for temperature dependence of electron collision frequency.

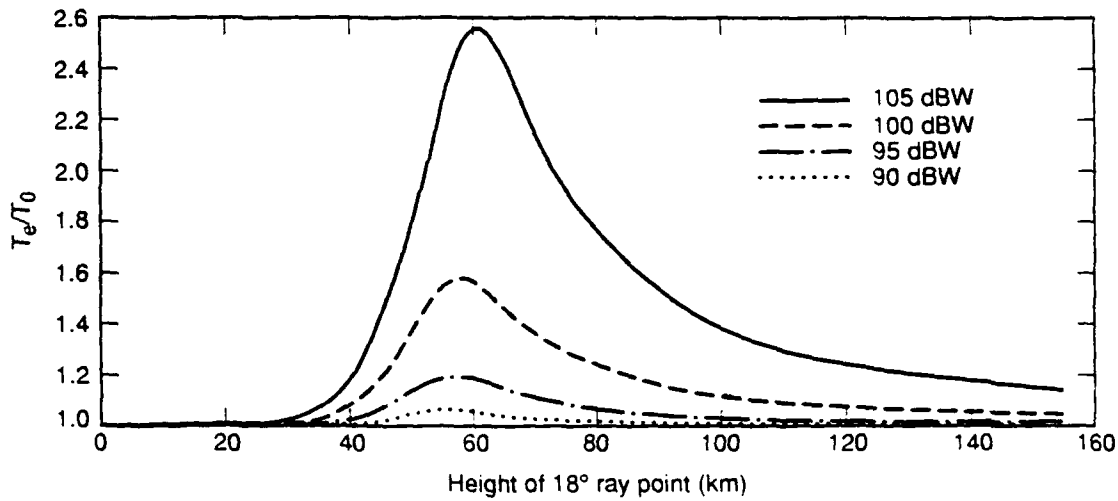


Figure 5. Change in electron temperature, T_e/T_0 , 15 MHz, 18° ray, daytime.

INCLUSION OF ELECTRON-DENSITY EFFECTS

An additional increase in the incremental absorption will be produced by changes in the factor N in Eq. (1). The electron density N will vary with electron temperature through the attachment and recombination rates.

From Knapp and Fischer [1970] we obtain the following expression for the steady state D-layer electron density N_e :

$$N_e \equiv \left[\sqrt{A^2 + 4q\alpha} - A \right] / 2\alpha \quad , \quad (3)$$

where

$q \sim 10^9 \text{ cm}^{-3} \text{ sec}^{-1}$ (photoelectron production rate)

$\alpha \sim 9 \times 10^{-3} T_e^{-1}$ (recombination coefficient)

$A \sim 5.4 \times 10^2 p^2 T_e^{-5/2} \exp[-540/T_e] + 1.3 \times 10^{-15} n[O] + 2.5 \times 10^{-12} n[O_3]$

$p \sim 10 \text{ dynes/cm}^2$ (pressure at 80 km) .

A is the electron-neutral attachment rate $n[O] \sim 10^{11}$, $n[O_3] \sim 10^8$ (molecular densities taken from Banks and Kockarts [1973]). The values given here are strictly empirical order-of-magnitude estimates.

Figure 6 shows the dependence of Eq. (3) on electron temperature T_e . The ambient temperature is $T_0 = 300^\circ \text{ K}$.

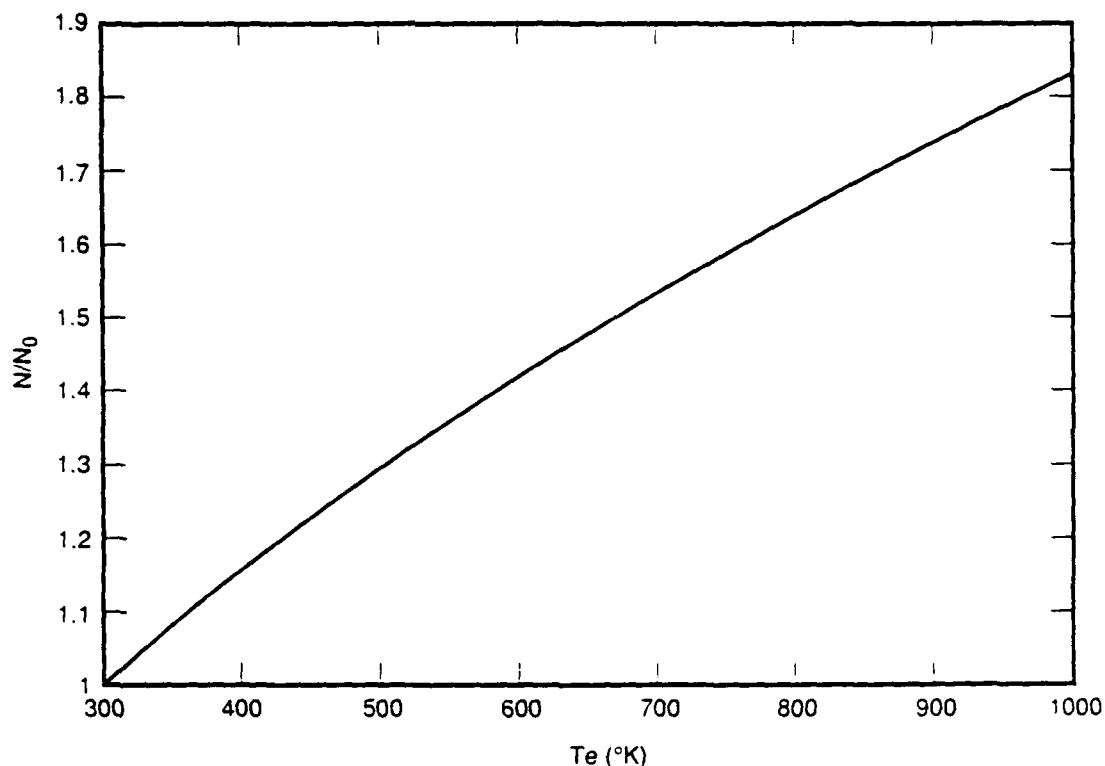


Figure 6. Dependence of electron density on temperature, $N(T_e)/N(T_0)$, daytime D-layer, $T_0 = 300$.

The result of including the temperature driven change N_e / N_0 in the electron density in the total absorption Eq. (1) is shown in Fig. 7, for the 105 dBW case only. The electron density increases at $z = 60 \text{ km}$ by about 50 percent due to the temperature dependence of the recombination and attachment rates. This affects the local incremental absorption and hence the integrated cumulative absorption. Figure 7, taken in combination with Fig. 4, indicates that a 15 dB increase in source power at the 90 dBW level is almost offset by the change in two-way collisional absorption caused by the 15 MHz wave itself.

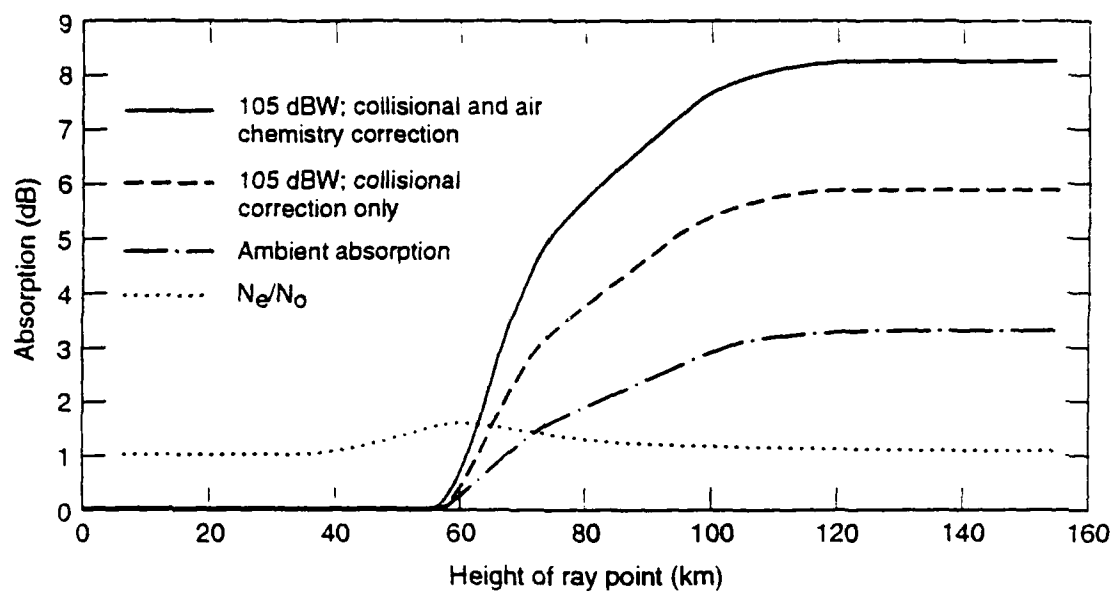


Figure 7. Corrected one-way absorption, 15 MHz, 18° ray, daytime.

CONCLUSION

Figure 7 shows that, at the 105 dBW ERP level, total one-way wave absorption is about 8 dB, nearly 5 dB greater than that predicted by the linear theory; 3 dB of this increase can be attributed to temperature dependence of the electron collision frequency, and the additional 2 dB is caused by temperature dependence of the electron-ion recombination processes.

Noting, from Fig. 4, that the total absorption at 90 dBW is nearly the same as in the linear theory, we see that increasing transmitter ERP by the additional 15 dBW yields about 16 dBW additional absorption along the two-way path. This is, we should emphasize, 16 dB more absorption than what the linear theory predicts. Thus, the point of diminishing returns in transmitter ERP is reached at 100 to 105 dBW. The implications of this limitation need to be further considered in high-power, HF, radio or radar system design.

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